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Performance of wind energy conversion systems using a cycloconverter to control a doubly fed induction generator

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Abstract

This paper is interested in the study of wind energy conversion systems (WECS) based on a doubly fed induction generator (DFIG) and a direct AC/AC cycloconverter. The dynamic behavior of the WECS, including the models of the wind turbine, the doubly fed induction generator, the cycloconverter, and the power control of this system, is studied. The power control of this system is applied to achieve the control of active and reactive powers exchanged between the stator of the DFIG and the grid, to ensure a maximum power point tracking (MPPT) of the WECS. The description for the proposed system is presented with the detailed dynamic modeling equations. Simulation results obtained on the basis of the dynamic models of the WECS are presented, to demonstrate the performance of the proposed system.

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Keywords: Wind energy conversion systems (WECS); Wind turbine; Doubly fed induction generator (DFIG); Cycloconverter; Power control; Maximum power point tracking (MPPT)

1. Introduction

In the recent years, renewable energy systems have attracted the great interest because conventional sources of energy are limited and a number of problems associated with their use, like environment pollution, large grid requirements etc. Governments of the whole world are forced for the alternative energy sources such as wind power, solar energy and small hydro-electric power [1]. Among the above given choices, wind energy is a realistic way of harnessing the natural energy. The use of the wind energy conversion systems has been significantly expending over the last few decades. This is due to the fact that this energy source of production of electricity is exhaust emission free [2].

Wind turbines can either operate at fixed-speed or variable-speed wind turbine. For a fixed-speed wind turbine the generator is directly connected to the electrical grid. For a variable-speed wind turbine the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines; among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power [3].

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The doubly fed induction generator is widely used for variable speed generation, and it is one of the most important generators for wind energy conversion systems. The main advantage of the DFIG is that the power electronics equipment only carries a fraction of the total power (20–30%) [4].

Cycloconverters are static frequency changers designed to convert constant voltage, constant frequency AC power to adjustable voltage adjustable frequency AC power without any intermediate DC link. The basic principle of a cycloconverter was proposed and patented by Hazeltine in 1926 [5]. Cycloconverters are suitable for large AC machines because it has advantages: it has high efficiency owing to the simple construction of the main circuit, which consists, in its basic form, simply of an array of thyristor switches [6], and it is also naturally commutative, and no forced commutation circuits are necessary.

In this paper, the proposed system is constituted of a DFIG with the stator connected directly to the grid while the rotor is supplied by a three phase cycloconverter. The performance of the system will be tested to improve the MPPT control and the control independent of the active and reactive powers using stator-flux oriented control technique.

This paper is organized as follows. The modeling of the wind turbine and the control of the MPPT are provided in Section 2. The DFIG is modeled in Section 3. The modeling of the cycloconverter is given in Section 4. The Power Control of a DFIG is developed in Section 5. Finally, the scheme of the studied WECS shown in Fig. 1 is simulated using Matlab/Simulink, the obtained results are presented and discussed.

2. Modeling of the wind turbine

The aerodynamic power, which is converted by a wind turbine, P_t is dependent on the power coefficient Cp.It is given by:

$$P_t = \frac{1}{2} \rho \, \pi \, R^2 \, C_p(\lambda) \, V^3 \tag{1}$$

Where ρ is the air density, R is the turbine radius, V is the wind speed.

The power coefficient Cp represents the aerodynamic efficiency of the wind turbine. It depends on the tip speed ratio λ. The tip speed ratio is given as:

$$\lambda = \frac{\Omega_t R}{V} \tag{2}$$

With Ω_t is the turbine speed.

For our example the power coefficient Cp is given by the following equation [7]:

$$C_p(\lambda) = 7{,}9563.10^{-5}.\lambda^5 - 17{,}375.10^{-4}.\lambda^4 + 9{,}86.10^{-3}.\lambda^3 - 9{,}4.10^{-3}.\lambda^2 + 6{,}38.10^{-2}.\lambda + 0{,}001 \tag{3}$$

Fig.2. illustrate the curve of $Cp(\lambda)$ obtained by equation (3).
The maximum value of $Cp(Cp\_max = 0.5483)$ is for $\lambda = 6.4$

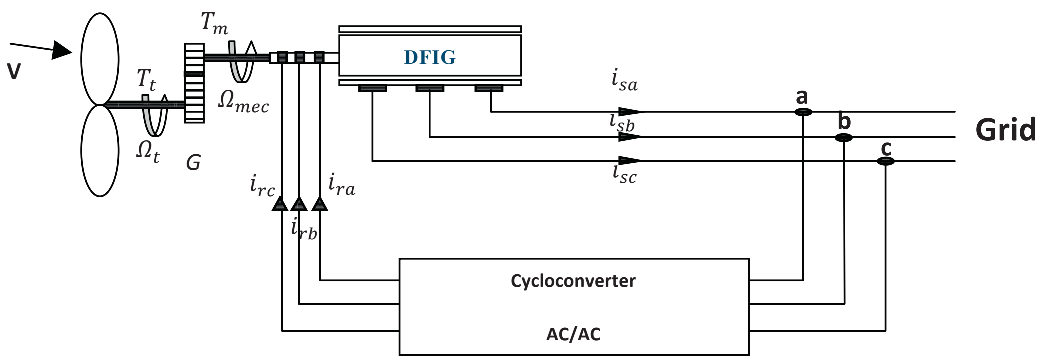

Fig. 1. Scheme of the studied device include the cycloconverter

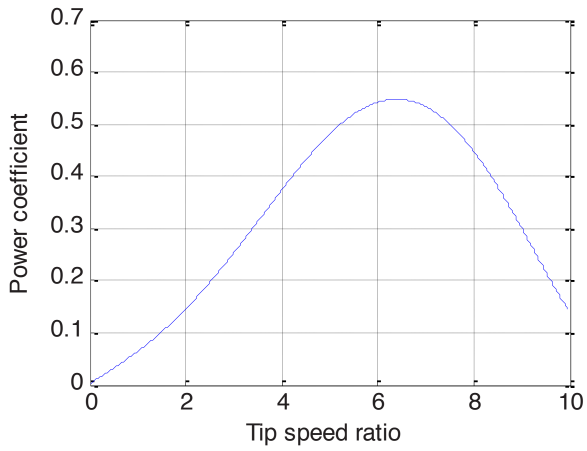

Fig. 2. Power coefficient for the wind turbine model

The turbine torque is the ratio between the output power of the turbine and the turbine speed:

$$T_t = \frac{P_t}{\Omega_t} \quad (4)$$

The torque of the turbine, referred to the generator side by the gearbox G, and the mechanical speed of the generator shaft, are given by:

$$T_m = \frac{T_t}{G} \quad and \quad \Omega_{mec} = \Omega_t\, G \quad (5)$$

The mechanical equation of the system can be characterized by:

$$J\frac{d\Omega_{mec}}{dt} = T_m - T_{em} - f\Omega_{mec} \quad (6)$$

Where J is the equivalent total inertia of the generator shaft, f is the equivalent total friction coefficient and T_{em} is the electromagnetic torque.

The action of the speed corrector must achieve two tasks [8]:

- It must control the mechanical speed Ω_{mec} in order to yet a speed reference Ω_{mec_ref}.
- It must attenuate the action of the aerodynamic torque, which is an input disturbance.

If the wind speed is measured and the mechanical characteristics of the wind turbine are known, it is possible to deduce in real time the optimal mechanical power which can be generated using the maximum power point tracking (MPPT).

Fig.3. represents the simplified diagram blocks of control speed.

3. Modeling of the DFIG

We used the classical modelization of the induction generator in the (d–q) Park reference frame [9]. The voltages and flux equations of the DFIG are:

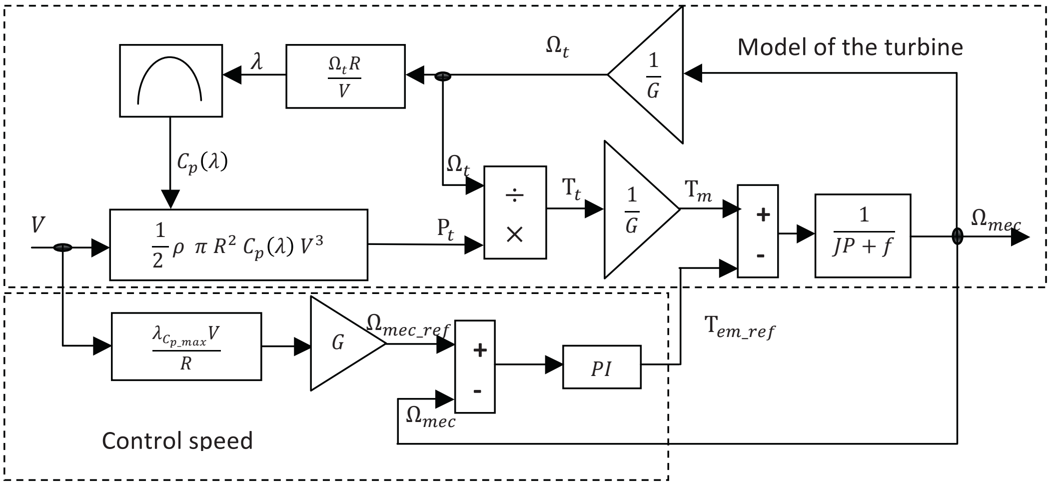

Fig. 3. MPPT with control of the speed

$$\begin{cases} V_{sd} = R_s i_{sd} + \frac{d}{dt}\phi_{sd} - \dot{\theta}_s \phi_{sq} \\ V_{sq} = R_s i_{sq} + \frac{d}{dt}\phi_{sq} + \dot{\theta}_s \phi_{sd} \\ V_{rd} = R_r i_{rd} + \frac{d}{dt}\phi_{rd} - \dot{\theta}_r \phi_{rq} \\ V_{rq} = R_r i_{rq} + \frac{d}{dt}\phi_{rq} + \dot{\theta}_r \phi_{rd} \end{cases} \tag{7}$$

$$\begin{cases} \phi_{sd} = L_s i_{sd} + M i_{rd} \\ \phi_{sq} = L_s i_{sq} + M i_{rq} \\ \phi_{rd} = L_r i_{rd} + M i_{sd} \\ \phi_{rq} = L_r i_{rq} + M i_{sq} \end{cases} \tag{8}$$

The active and reactive powers equations at the stator are written as:

$$\begin{cases} P_s = V_{sd} i_{sd} + V_{sq} i_{sq} \\ Q_s = V_{sq} i_{sd} - V_{sd} i_{sq} \end{cases} \tag{9}$$

And the electromagnetic torque is expressed as:

$$T_{em} = p\left(\phi_{sd} i_{sq} - \phi_{sq} i_{sd}\right) \tag{10}$$

4. Modeling of the cycloconverter

A cycloconverter consists of one or more pairs of back to back connected controlled rectifiers. The delay angles of those rectifiers are modulated so as to provide an AC output voltage at the desired frequency and amplitude.

The rotor is supplied by a three phase cycloconverter. The simplified three phases - three phases cycloconverter topology is shown in Fig.4 .The cycloconverter is composed of 18 thyristors. Each phase is composed of two back to back rectifiers. The one that conducts the positive current is called a P converter, and the one that conducts the negative current is called an N converter. The cycloconverter has natural commutation without circulating current. All the thyristors are supposed as idealized. This configuration enables the connection of any input phase a, b or c to any output phase A, B or C at any instant. This cycloconverter is low enough in cost for general purpose use.

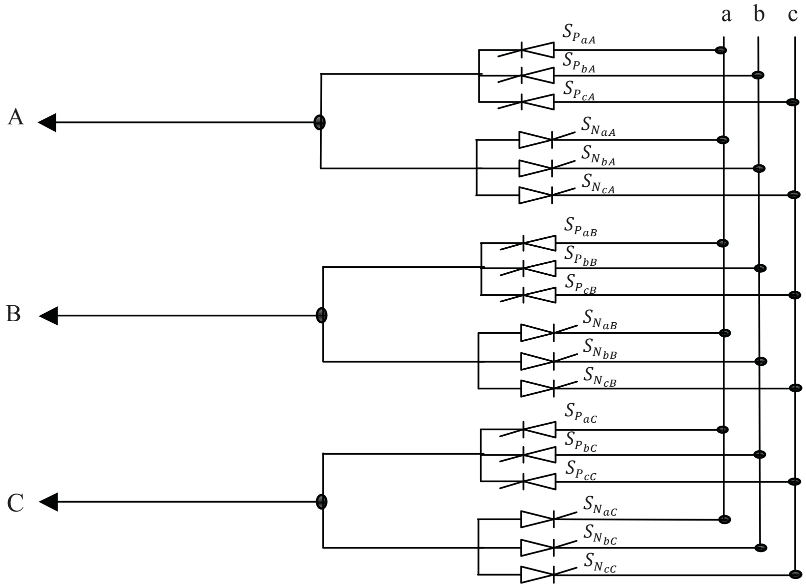

Fig. 4. Model of the cycloconverter

The switching function in Fig. 4 is defined as:

$$S_{K_{ij}} = \begin{cases} 1 & S_{K_{ij}} \textit{ is closed} \\ 0 & S_{K_{ij}} \textit{ is open} \end{cases} \qquad K \in \{P, N\}\,,\;\; i \in \{a, b, c\}\,,\;\; j \in \{A, B, C\}$$

And

$$S_{P_{aj}} + S_{P_{bj}} + S_{P_{cj}} + S_{N_{aj}} + S_{N_{bj}} + S_{N_{cj}} = 1 \tag{11}$$

In order to control the output voltage of the cycloconverter, the phase-angle control is needed for commanding the thyristor firing pulses. In this paper, cosine-wave control is selected for producing firing pulses. So we will have three timing waves and three reference waves and a lot of intersection points. We have 18 control circuits for this cycloconverter one for each thyristor. The three phase cycloconverter can be represented by a 3x3 matrix for because switches can connect directly without any intermediate energy storage elements. Therefore, the output voltage of the cycloconverter can be represented by the transfer function [T] such as:

$$\begin{bmatrix} v_A \\ v_B \\ v_C \end{bmatrix} = \begin{bmatrix} \left(S_{P_{aA}} + S_{N_{aA}}\right) & \left(S_{P_{bA}} + S_{N_{bA}}\right) & \left(S_{P_{cA}} + S_{N_{aA}}\right) \\ \left(S_{P_{aB}} + S_{N_{aB}}\right) & \left(S_{P_{bB}} + S_{N_{bB}}\right) & \left(S_{P_{cB}} + S_{N_{aB}}\right) \\ \left(S_{P_{aC}} + S_{N_{aC}}\right) & \left(S_{P_{bC}} + S_{N_{bC}}\right) & \left(S_{P_{cC}} + S_{N_{cC}}\right) \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{12}$$

$$[v_{ABC}] = [T][v_{abc}] \tag{13}$$

Where

v_a, v_b and v_c are, respectively, the input phase voltages.

v_A, v_B and v_C are, respectively, the Output phase voltages.

5. Power control

In this section, the DFIG model can be described by the following state equations in the synchronous reference frame whose axis d is aligned with the stator flux vector ϕ_{sd}, ($\phi_{sd} = \phi_s$ and $\phi_{sq} = 0$) [10].The control of the DFIG must allow a control independent of the active and reactive powers by the rotor voltages generated by the cycloconverter using a stator-flux oriented control technique.

By neglecting resistances of the stator phases the stator voltage will be expressed by:

$V_{sd} = 0$ and $V_{sq} = V_s \approx \omega_s \phi_s$

The expressions of the statoric currents are written as:

$$\begin{cases} i_{sd} = \dfrac{\phi_{sd} - M i_{rd}}{L_s} \\ i_{sq} = \dfrac{-M}{L_s} i_{rq} \end{cases} \tag{14}$$

By replacing these currents in the rotor fluxes equations, we obtain:

$$\begin{cases} \phi_{rd} = L_r \sigma i_{rd} + \dfrac{M}{L_s} \phi_{sd} \\ \phi_{rq} = L_r \sigma i_{rq} \end{cases} \tag{15}$$

σ is the leakage coefficient, defined by:

$$\sigma = 1 - \frac{M^2}{L_s L_r} \tag{16}$$

The rotor voltages can be written according to the rotor currents as:

$$\begin{cases} V_{rd} = R_r i_{rd} + L_r \sigma \dfrac{di_{rd}}{dt} + -s\omega_s L_r \sigma i_{rq} \\ V_{rq} = R_r i_{rq} + L_r \sigma \dfrac{di_{rq}}{dt} + s\omega_s L_r \sigma i_{rd} + s\omega_s \dfrac{M}{L_s} \phi_{sd} \end{cases} \tag{17}$$

s is the slip of the DFIG.

Then the electromagnetic torque is simplified into:

$$T_{em} = -P \frac{M}{L_s} \phi_{sd} i_{rq} \tag{18}$$

And the active and reactive stator powers of the DFIG are expressed by:

$$\begin{cases} P_s = -V_s \dfrac{M}{L_s} i_{rq} \\ Q_s = \dfrac{V_s^2}{\omega_s L_s} - V_s \dfrac{M}{L_s} i_{rd} \end{cases} \tag{19}$$

The detailed scheme of the studied WECS is presented in Fig. 5.

6. Results and interpretation

We present the simulation, using Matlab/Simulink, of the DFIG connected directly to the grid through the stator, and controlled through its rotor circuit.

The DFIG used in this work is a 7.5 kW, whose nominal parameters are indicated in appendix A.
The wind speed is 8.5 m/s shows in Fig. 6a.
Fig. 6b shows the mechanical speed of the DFIG.

Fig. 7 shows the stator current, stator voltage and their zoom at a constant frequency of 50 Hz.
The rotor current, rotor voltage and their zoom are showed in Fig. 8.
Fig. 9 presents the stator active and reactive powers of the DFIG and their reference.

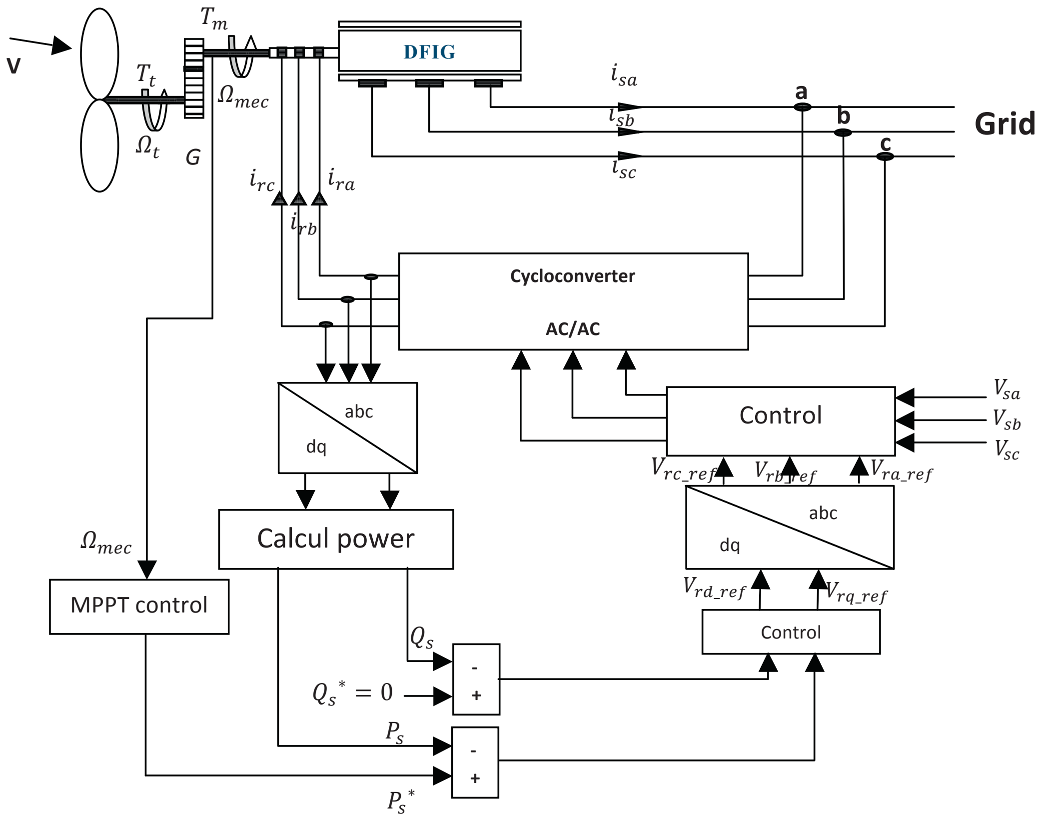

Fig. 5. Detailed diagram of the studied device

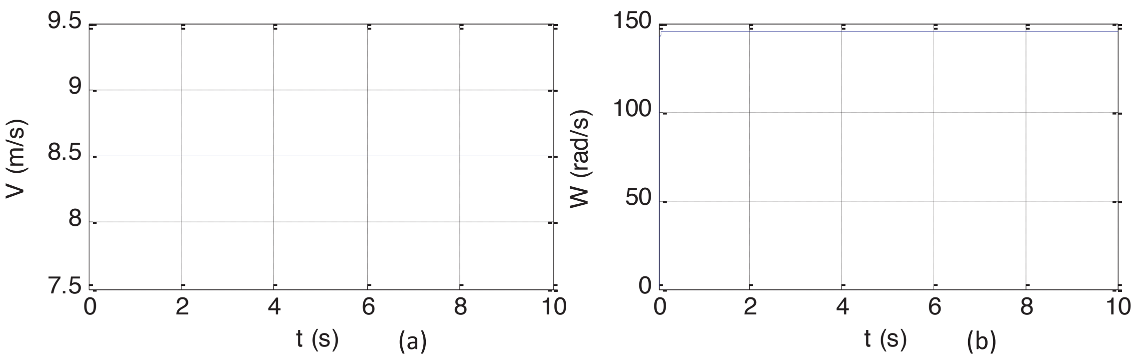

Fig. 6. (a) Wind turbine speed; (b) Mechanical speed of the DFIG

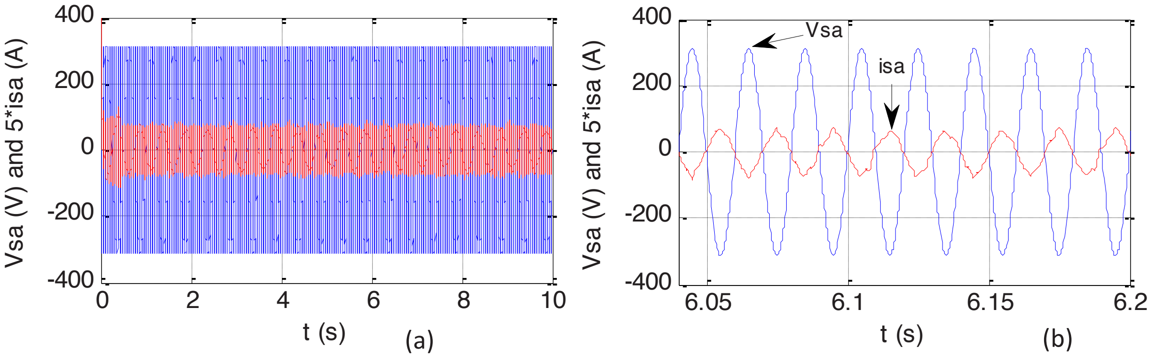

Fig. 7. (a) Stator voltage and current; (b) Zoom Stator voltage and current

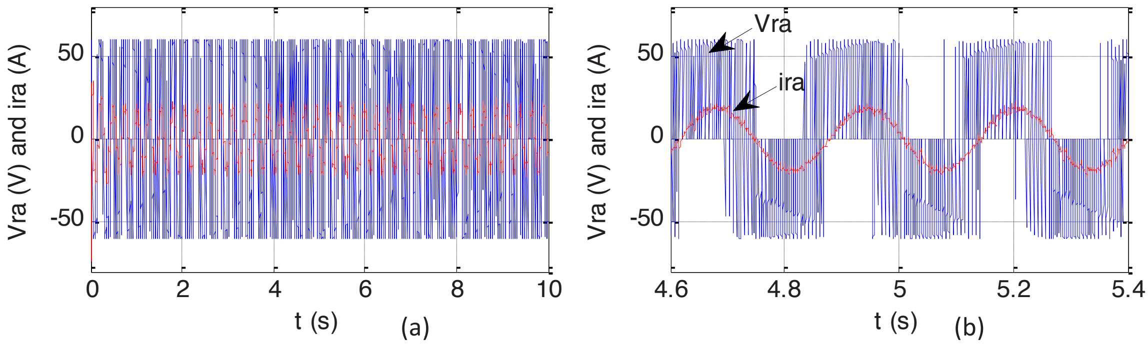

Fig. 8. (a) Rotor voltage and current; (b) Zoom Rotor voltage and current

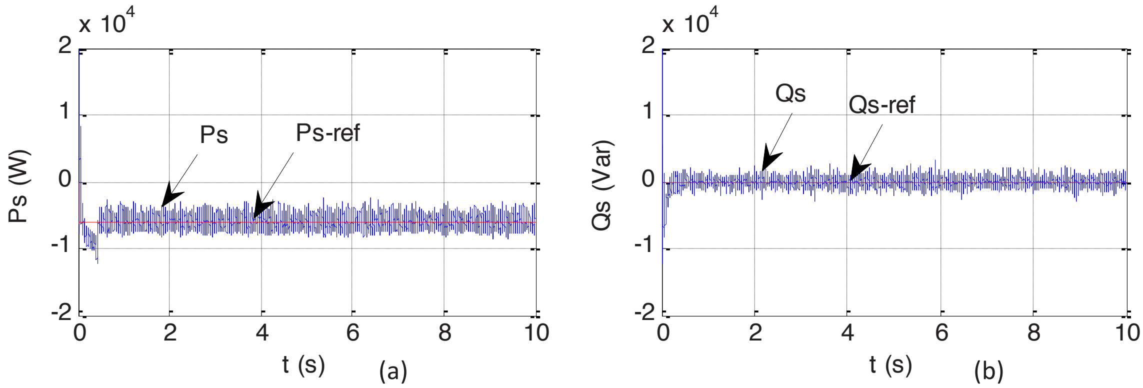

Fig. 9. (a) Stator active power; (b) Stator Reactive power

The rotor current and voltage showed in Fig. 8 validates the control of the cycloconverter. In Fig. 9 the stator active and reactive powers follow their references perfectly. Moreover, as can be seen from Fig. 9 the stator active and reactive powers can be controlled independently. The stator active power injected into the grid is controlled according to the MPPT strategy, when the reactive power is maintained to zero, to guarantee a unity power factor at the stator side. The zoom of the stator current and voltage (Fig. 7b) validates the unity power factor of the WECS.

7. Conclusion

In this work, we have presented a complete WECS made with a doubly fed induction generator and a cycloconverter. This system is constituted of a DFIG with the stator connected directly to the grid while the rotor is supplied by a three phase cycloconverter. The maximum power point tracking performance of the system is tested. The stator active and reactive powers are controlled independently through the cycloconverter by using a stator-flux oriented control technique. Simulation results show good decoupling and performance between stator active and reactive powers and guarantee the unity power factor. In general the DFIG based WECS are more efficient and can capture more energy from the wind. Therefore, in this paper, the DFIG with the cycloconverter based on WECS are proved the efficiency and reduced the cost. Finally, the proposed system is this paper is feasible and has many advantages. It may be considered as an interesting way for problems solution in renewable energy area.

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Appendix A. Parameters

Turbine: Power = 10 (KW), R = 3 (m), number of blades = 3, gearbox= 8.

DFIG: Power = 7.5 (KW), p = 2, R_s= 0.455 (Ω), R_r= 0.62 (Ω), L_s = 0.084 (H), L_r = 0.081 (H), M= 0.078(H)

J =0.3125 $(\mathrm{Kg.m^2})$and f = 0.00673 $(\mathrm{N.m.s})$.

Appendix B. Nomenclature

V_{sd}, V_{sq}, V_{rd}, V_{rq}	Stator and rotor voltages in the (d–q) reference frame
i_{sd}, i_{sq} , i_{rd} , i_{rq}	Stator and rotor currents in the (d–q) reference frame
ϕ_{sd}, ϕ_{sq} , ϕ_{rd}, ϕ_{rq}	Stator and rotor flux in the (d–q) reference frame
θ_s, θ_r	Stator and rotor field angles
R_s, R_r	Stator and rotor resistances
L_s, L_r	Cyclic stator and rotor inductances

M	Cyclic mutual inductance
ω_s	Stator pulsation
p	Number of pole pairs